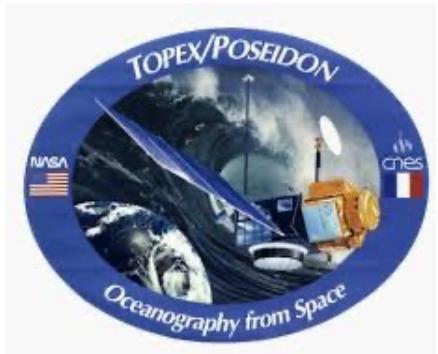


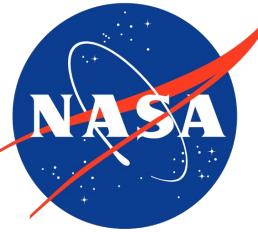
The status of the NASA GSFC altimeter satellite orbits for TOPEX, the Jason satellites and Sentinel-6A

F. G. Lemoine (1), N.P. Zelensky (2), B.D. Beckley (3), X. Yang (3), D.S. Chinn (3),
T. C. Thomas (4), S. B. Luthcke (1), T. A. Pennington (3), D.D. Rowlands (1)

- (1) NASA GSFC, Greenbelt, Maryland, U.S.A.
- (2) UMD/ESSIC, College Park, Maryland, U.S.A.
- (3) KBR Inc., Greenbelt, Maryland, U.S.A.
- (4) Science Systems and Applications (SSAI), Inc., Greenbelt, Maryland, U.S.A.

2023 Ocean Surface Topography Science Team Meeting
San Juan, Puerto Rico, U.S.A.,
November 7 – 11, 2023





GSFC SLR+DORIS nominal POD Strategy and the 4 Tests

| model | std2006_cs21 | Test |
|-------------------------|--|--|
| gravity | GSFC 5x5 series or 4x4 model + GOCO05s | 1) GRGS_RL05 (1992-2023), 2) COSTG_FSM(2018-2023) |
| atmosphere gravity | GFZ 90X90 3-hr from ECMWF (cf. GRACE FO, RL06) | |
| Geocenter | Annual model (ITRF2014) | 3) Annual + semi-annual (ITRF2020) |
| mean pole | IERS2017 (linear mean pole) | |
| integration step size | 15 seconds | |
| S6A Solar Rad. Pressure | new TSI, tuned Cr/arc, CNES 6-panel macromodel | 4) Conrad 12-panel macromodel |
| DORIS Coordinates | DPOD2014 Version 5.5 (August 2021) | 3) DPOD2020 |
| DORIS SAA Stations | J1, J3, S6A, downweighted by 3X | |
| elev. cutoff (DORIS) | 10 deg. | |
| DORIS data weighting | elevation-dependent (J2, J3, S6A) | |
| SLR Coordinates | SLRF2014 (v200428). | 3) SLRF2020 |
| SLR Data Handling | SLRF2014 with T2L2-derived corrections. | |
| LRA phase center | constant + elevation correction. | |
| SLR bias strategy | gsfc2020 (from ILRS, 06-16-2020) | 3) estimate station range per arc |
| OPR parameters | per 24-hr (along + cross-track) | |



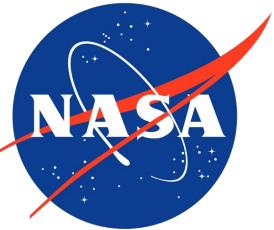
| Test name | Description (and test period) |
|-------------------|---|
| std2006_cs21 | Nominal (ITRF2014-based complements) (1992-2023) |
| std2300 | as std2006_cs21 plus ITRF2020-based complements (1992-2023) |
| std2300_grgs_rl05 | as std2300 using the CNES GRGS_RL05 gravity (1992-2023) |
| std2300_costg_fsm | as std2300 using the COSTG FSM gravity (2018-2023) |
| std2300_conrad | as std2300 using the Sentinel-6a Conrad 12-panel macromodel |

- Std2006_cs21 is the current series (based on ITRF2014)
- Std2300_XXX are the different candidate test series all based on ITRF2020.

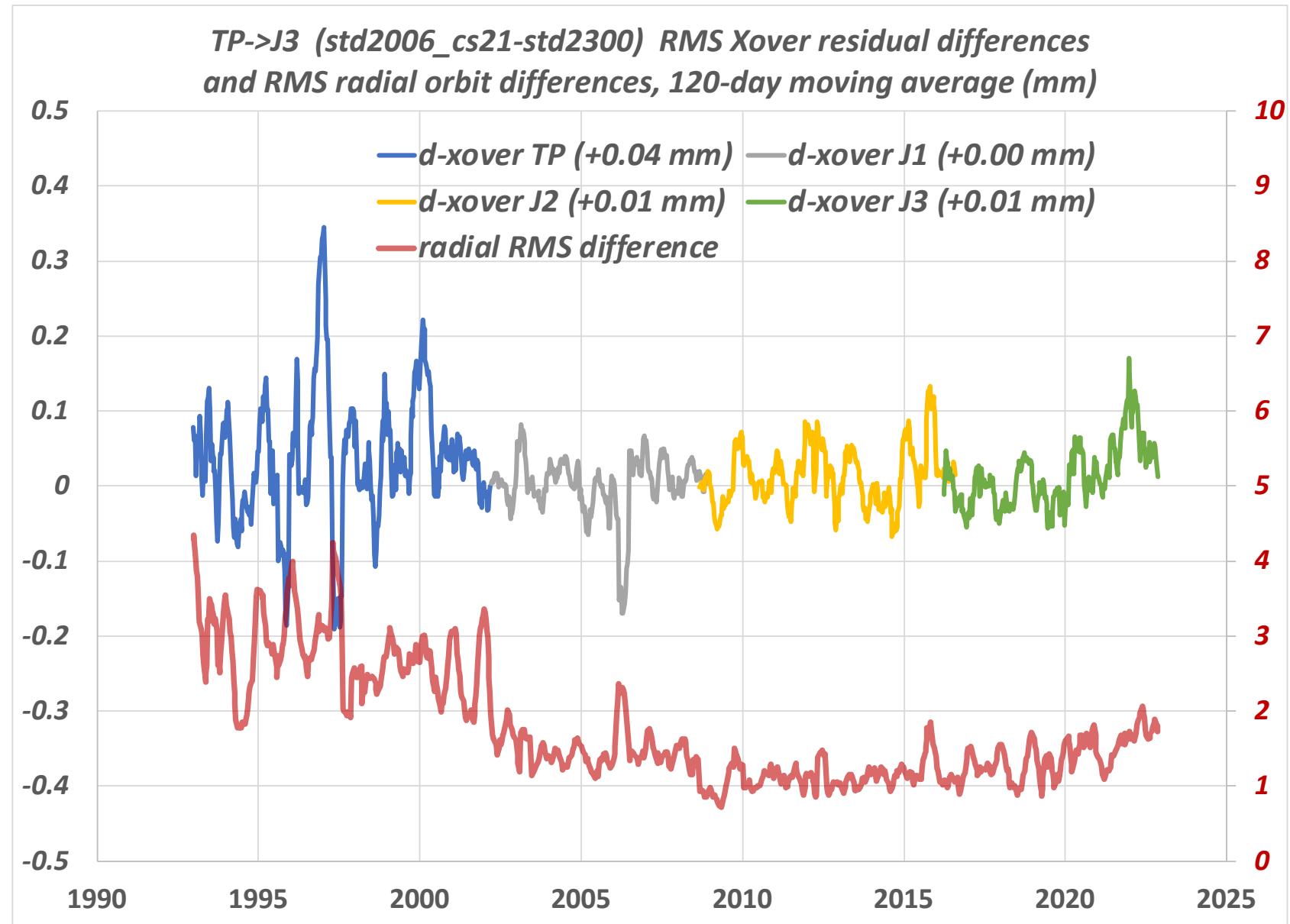


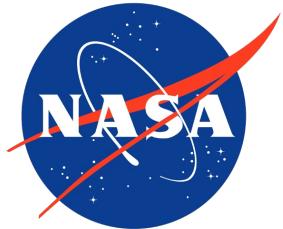
GSFC SLR+DORIS dynamic POD tests

| Test /span | Test Name, Description | Nominal Name, Description |
|---|---|---|
| Reference Frame 921101 -> 231004 (TP -> S6A) | 1) std2300 (ITRF2020-based) DPOD2020, SLRF2020 complements SLR range bias: est. station bias/arc | std2006_cs21 (ITRF2014-based) DPOD2014, SLRF2014 complements SLR range bias: ILRS Data Handling file |
| Gravity GRGS 921101 -> 231004 (TP -> S6A) | 2) std2300_grgs_rl05 CNES GRGS RL05 90x90 TVG + 91x180 static | std2300 GSFC 5X5 gravity series or 4x4 model plus GOCO05s background (5x100 TVG + 100x180 static) |
| Gravity COSTG 180101 -> 231004 (J3, S6A) | 3) std2300_costg_fsm COSTG-FSM 90x90 TVG + GOCO06s 91x180 static | std2300 (gravity as above) |
| S6A SRP model 201218 -> 231004 (S6A) | 4) std2300_Conrad Conrad et al, 2022 12-panel macromodel | std2300 CNES 6-panel macromodel |



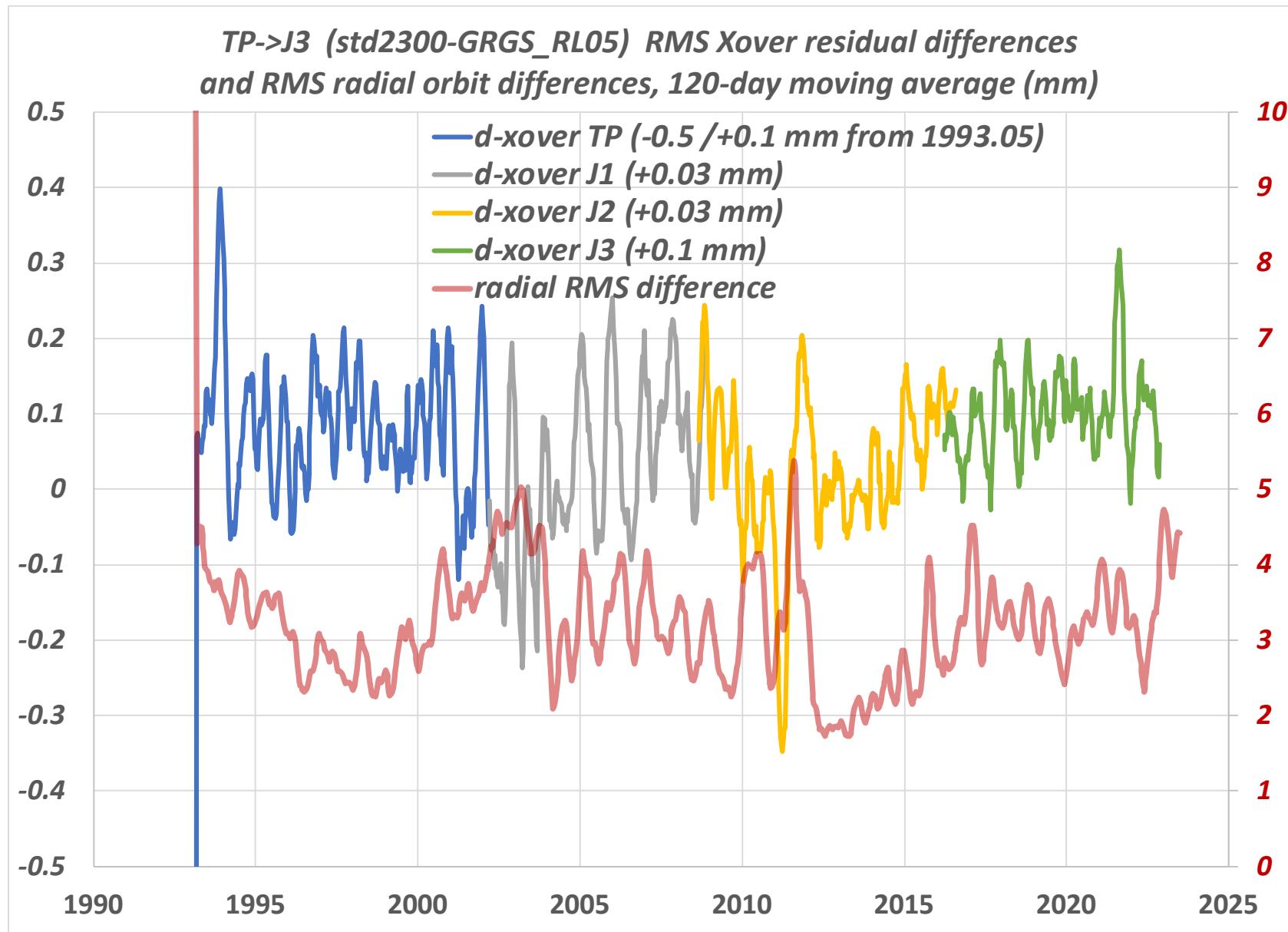
Test of the Reference Frames: ITRF2014-based –vs– ITRF2020-based POD d-xover (left axis) positive => improvement for ITRF2020-based POD

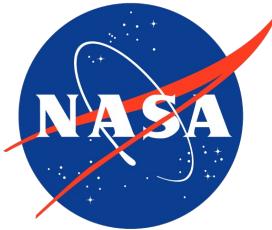




Tests of the Gravity fields: GSFC std2300 –vs- CNES GRGS_RL05 (1 of 2)

d-xover (left axis) positive => improvement for GRGS_RL05 POD





Tests of the Gravity fields: GSFC std2300 –vs- CNES GRGS_RL05 (2 of 2)

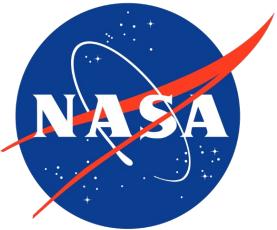
| Mission | Gravity field | POD residuals | | Xover residuals (cm) | Radial orbit RMS difference (mm) | |
|----------------------------|---------------|-----------------|--------------|-------------------------|-------------------------------------|---------|
| | | DORIS (mm/s) | SLR (mm) | | poef | std2300 |
| TOPEX (930120-041101) | std2300 | 0.5125 | 14.73 | 5.602 | 8.8 | ---- |
| | GRGS RL05 | 0.5125 | 14.79 | 5.596 | 8.6 | 3.3 |
| Jason-1 (020115-090126) | std2300 | 0.3883 | 0.758 | 5.486 | 7.5 | ---- |
| | GRGS RL05 | 0.3883 | 0.772 | 5.483 | 7.2 | 3.5 |
| Jason-2 (080712-161002) | std2300 | 0.3906 | 7.09 | 5.292 | 6.2 | ---- |
| | GRGS RL05 | 0.3906 | 7.09 | 5.292 | 6.2 | 2.8 |
| Jason-3 (160217-230828) | std2300 | 0.3911 | 5.85 | 5.166 | 6.1 | ---- |
| | GRGS RL05 | 0.3909 | 5.81 | 5.157 | 5.9 | 3.4 |



POD with the three Gravity fields from 2018: Jason-3 & Sentinel-6A

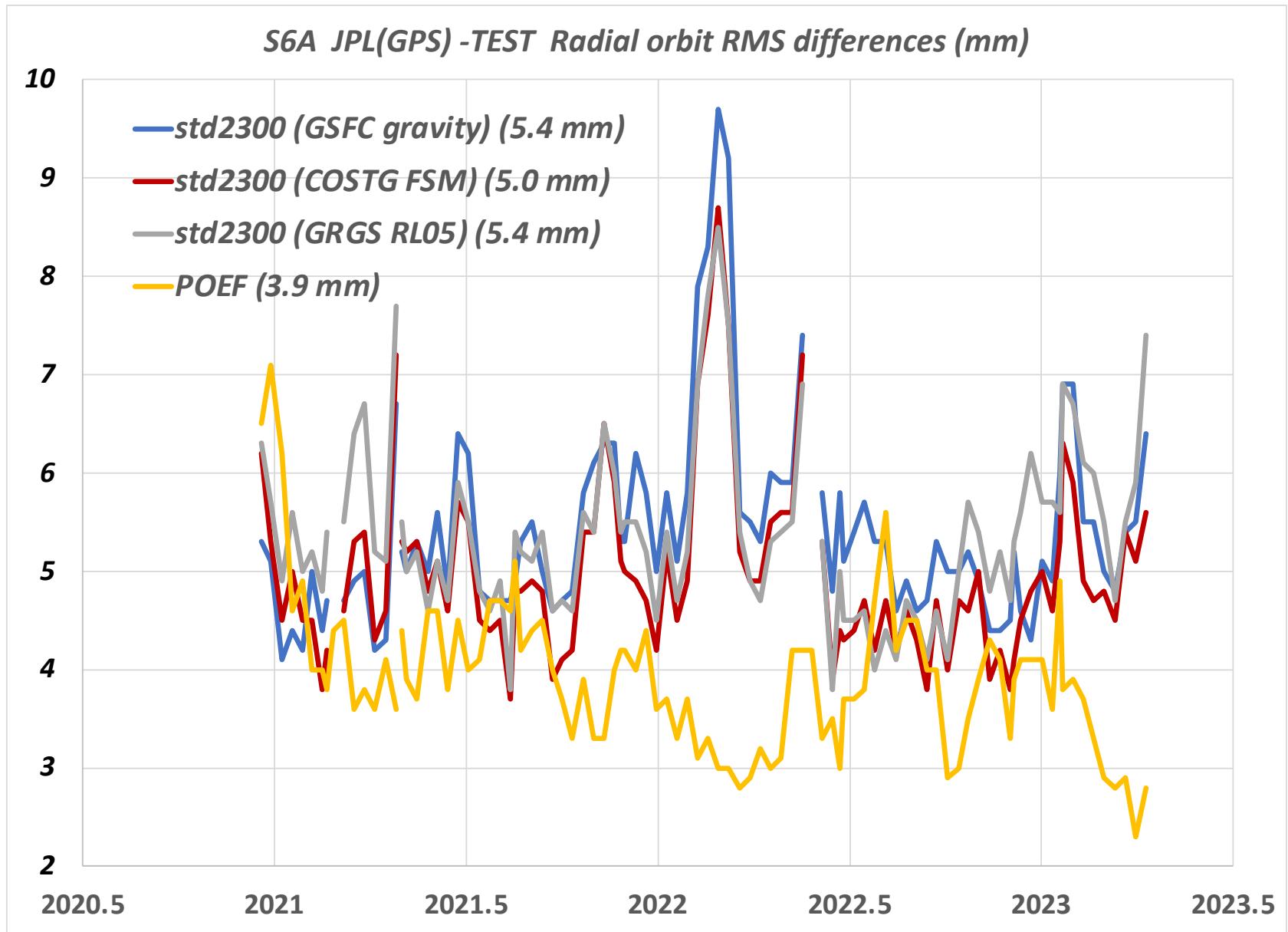
| Jason-3 tests (180101-230828) | POD residuals | | Xover residuals to 230619 (cm) | Radial orbit RMS difference (mm) | | |
|----------------------------------|-----------------|-------------|---|-------------------------------------|---------------------|---------|
| | DORIS (mm/s) | SLR (mm) | | poef | jpl22a to 220328 | std2300 |
| std2300 | 0.3904 | 5.80 | 5.171 | 6.2 | 5.4 | ---- |
| std2300 GRGS RL05 | 0.3903 | 5.75 | 5.161 | 5.8 | 5.1 | 3.4 |
| std2300 COSTG FSM | 0.3910 | 5.62 | 5.162 | 5.7 | 5.1 | 2.9 |

| Sentinel-6A tests (201218-231004) | POD residuals | | Radial orbit RMS difference (mm) | | |
|--------------------------------------|---------------|----------|----------------------------------|------------------|---------|
| | DORIS (mm/s) | SLR (mm) | poef | jpl to 230419 | std2300 |
| std2006_cs21 | 0.3858 | 6.36 | 6.7 | 6.0 | 1.8 |
| std2300 | 0.3847 | 6.19 | 6.7 | 5.7 | ---- |
| std2300 GRGS RL05 | 0.3848 | 6.31 | 6.5 | 5.7 | 3.7 |
| std2300 COSTG FSM | 0.3847 | 5.92 | 6.1 | 5.3 | 3.0 |



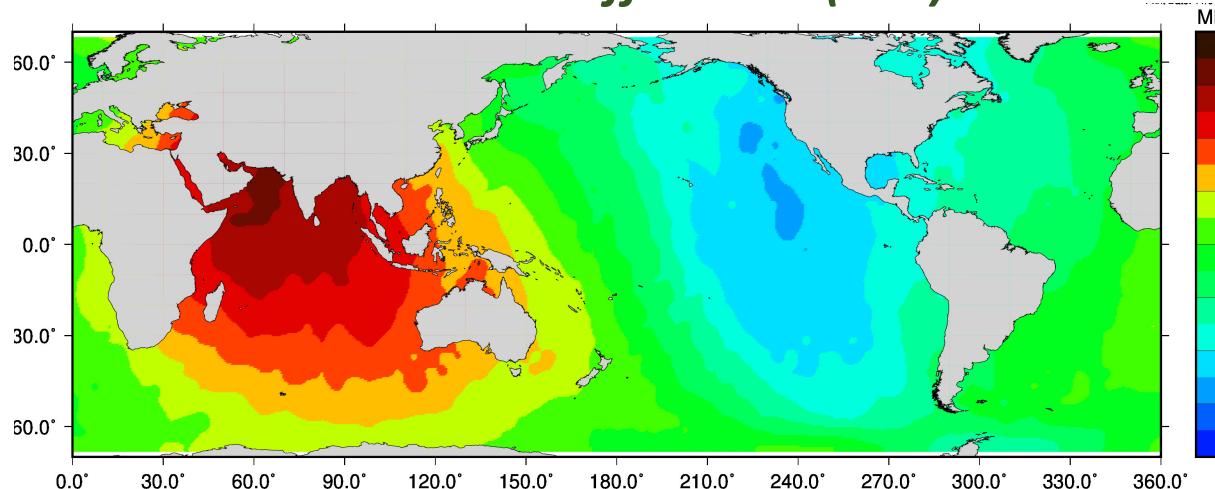
Gravity field impact on Sentinel-6A orbit (1 of 2)

JPL-Test radial RMS orbit differences (mm)

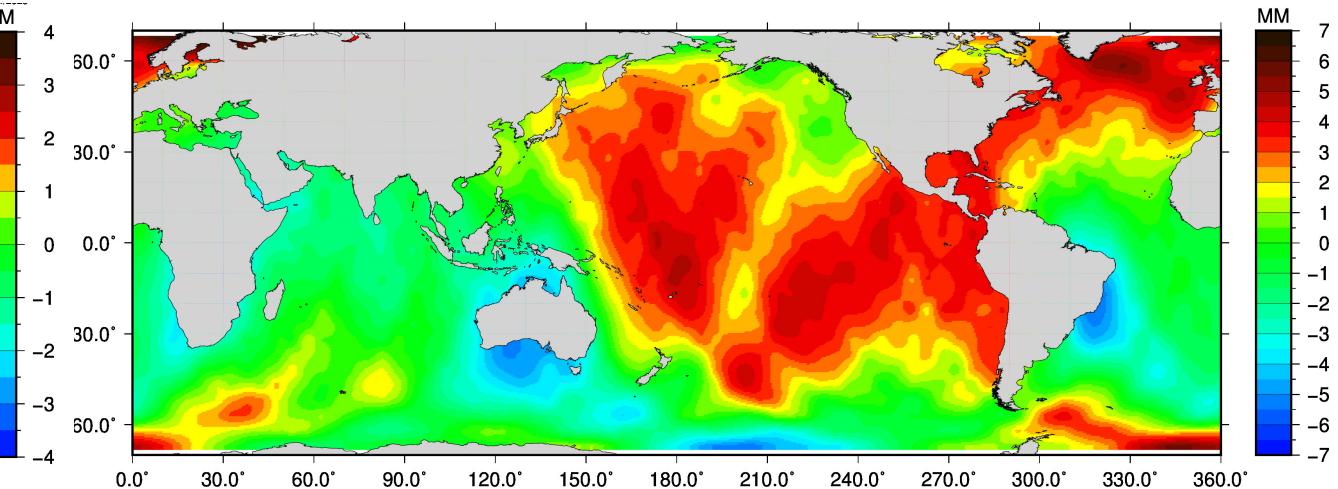


*Gravity field impact on Sentinel-6A orbit (2 of 2)
geographically-correlated radial error (201218-230419 or cycles 4-89)*

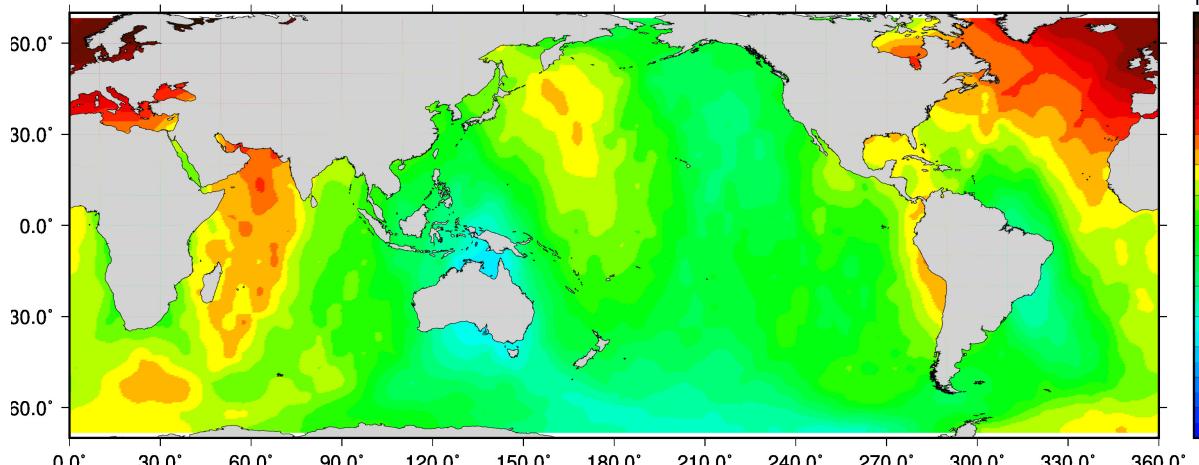
*JPL-GSFC std2300 gravity geographically-binned
radial orbit differences (mm)*



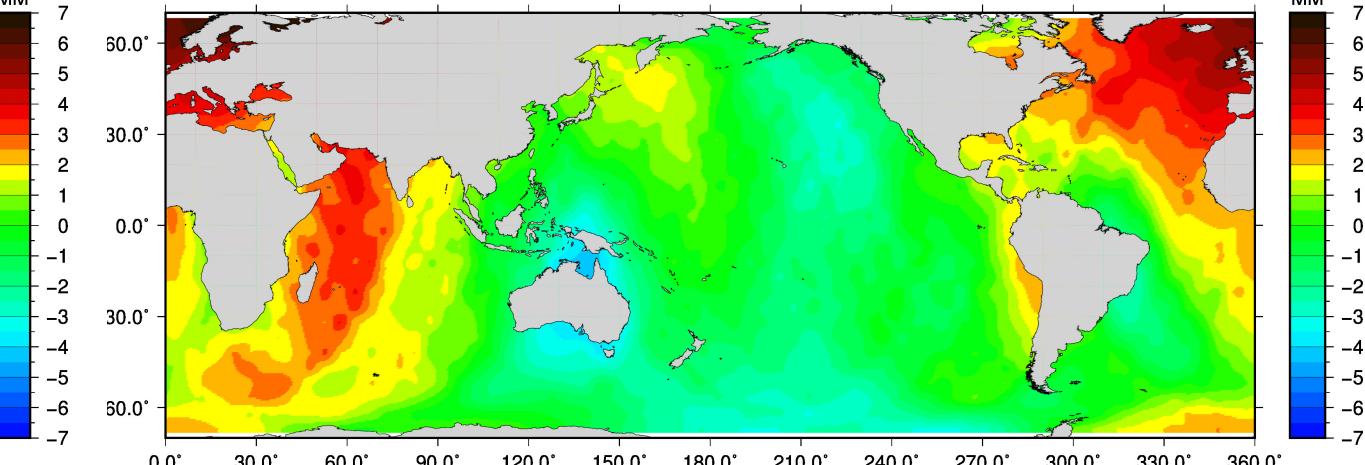
*JPL- CNES POEF gravity geographically-binned
radial orbit differences (mm)*



*JPL- GSFC COSTG_FSM gravity geographically-binned
radial orbit differences (mm)*

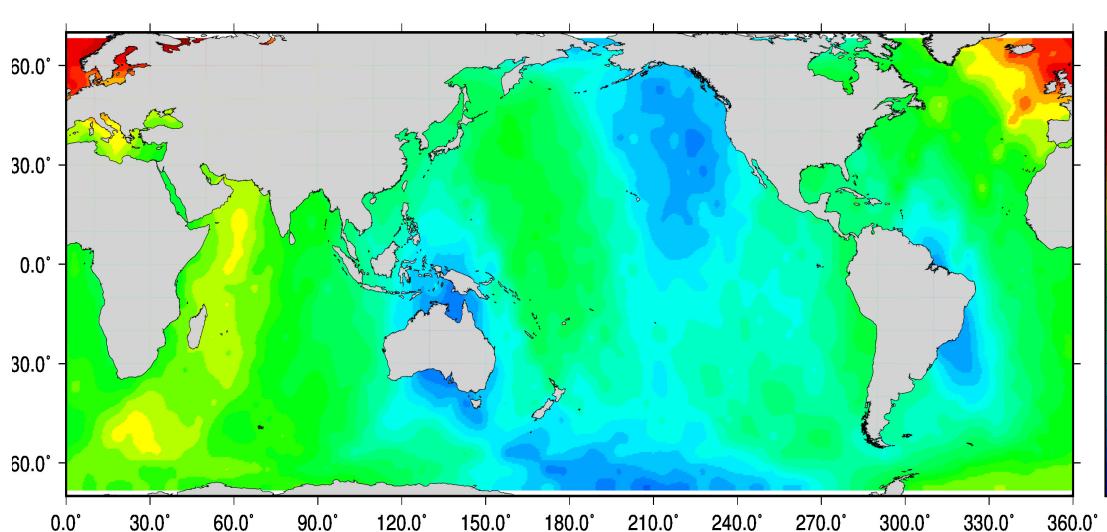


*JPL- GSFC GRGS_RL05 gravity geographically-binned
radial orbit differences (mm)*

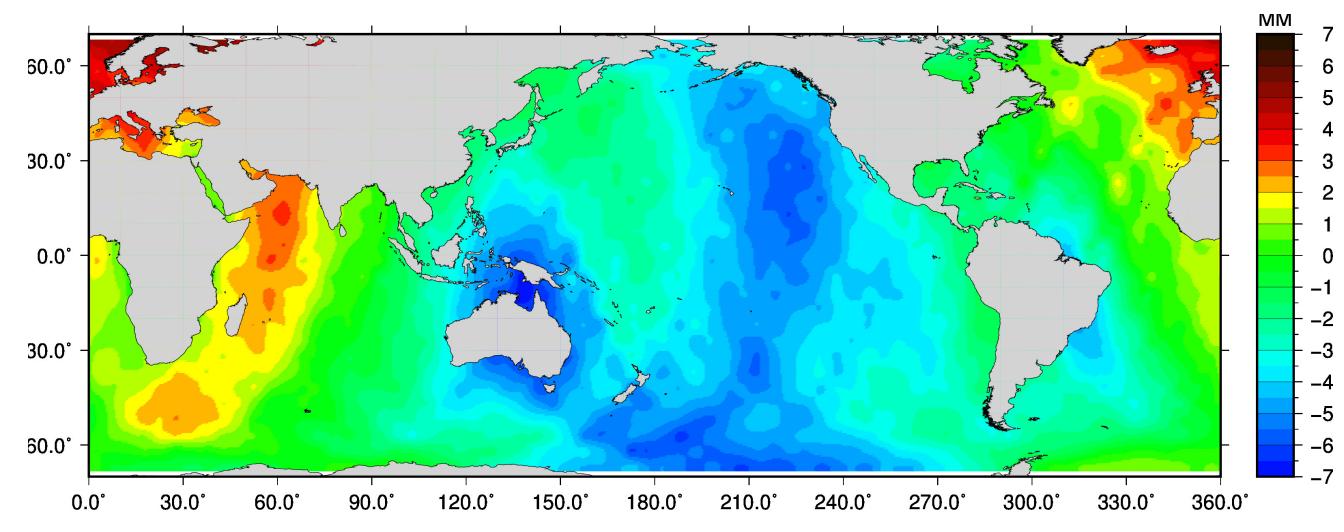


*Gravity field impact on Jason-3 / Sentinel-6A orbits
geographically-binned radial orbit differences (mm) (201218-220408)*

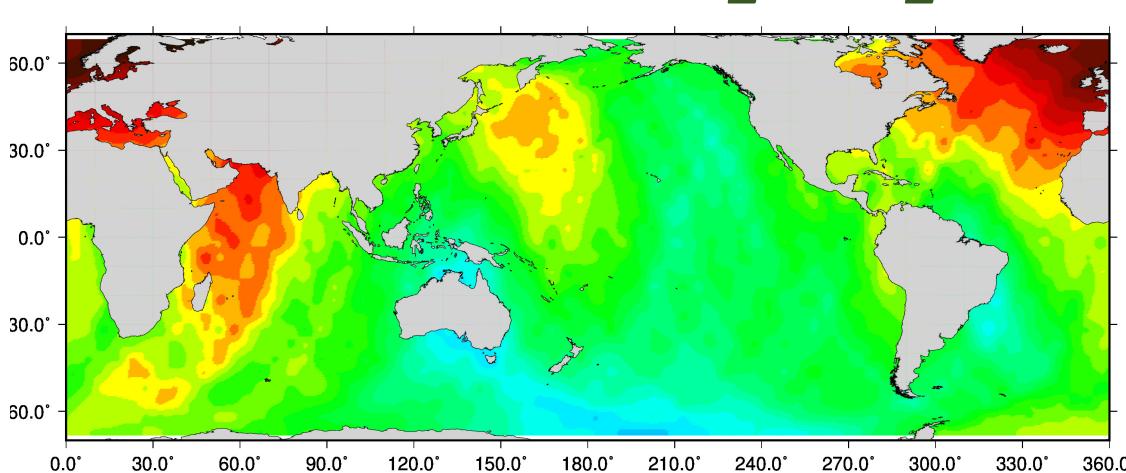
Jason3 JPL22a - GSFC std2300 COSTG FSM orbits



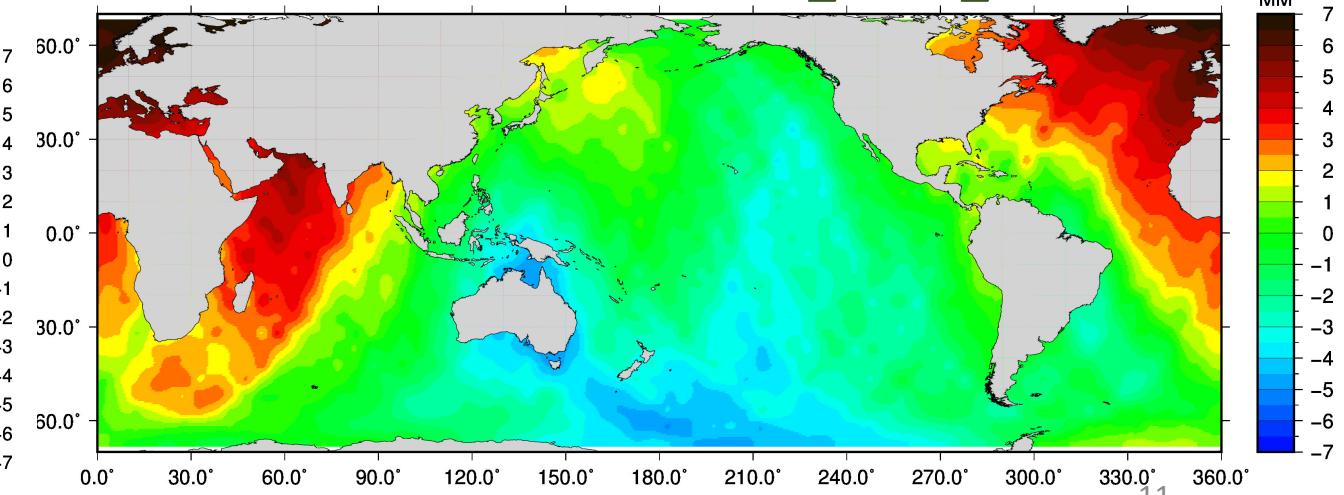
Jason3 JPL22a - GSFC std2300 GRGS RL05 orbits

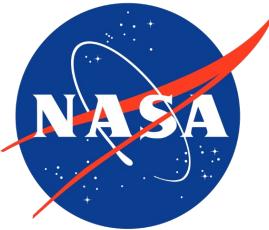


Sentine-6A JPL - GSFC std2300 COSTG FSM orbits

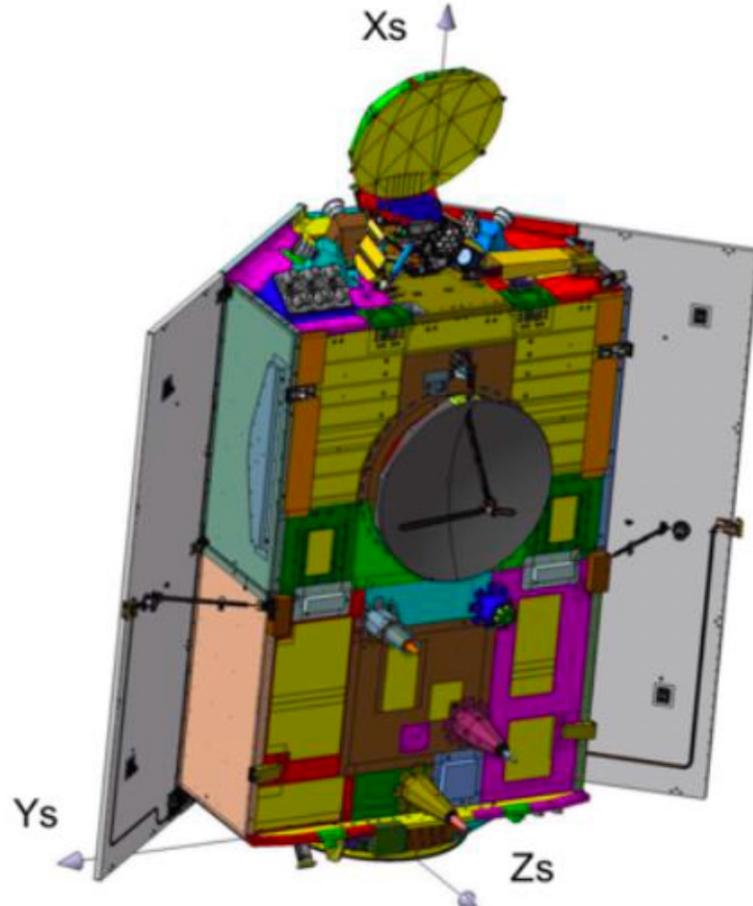


Sentine-6A JPL - GSFC std2300 GRGS RL05 orbits





Sentinel-6A CNES 6-panel and Conrad 12-panel macromodels

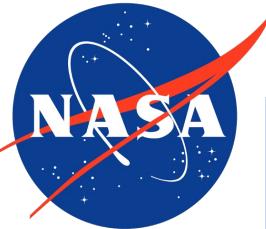


CNES 6-panel (only optical properties used)

| | // Optical properties | | | | // Infrared properties | | | |
|---|-----------------------|---------|--------|---------|------------------------|--------|--|--|
| // Surf(m ²) // Normal in sat ref frame | // spec | // diff | // abs | // spec | // diff | // abs | | |
| 3.600 -1. 0. 0. | 0.4500 | 0.1200 | 0.4300 | 0.1800 | 0.0400 | 0.7800 | | |
| 3.370 1. 0. 0. | 0.4590 | 0.5410 | 0.0000 | 0.1920 | 0.8080 | 0.0000 | | |
| 8.660 0. -0.6157 -0.7880 | 0.0000 | 0.3370 | 0.6630 | 0.0000 | 0.6150 | 0.3850 | | |
| 8.660 0. 0.6157 -0.7880 | 0.0000 | 0.3370 | 0.6630 | 0.0000 | 0.6150 | 0.3850 | | |
| 2.990 0. 0. -1. | 0.4550 | 0.5110 | 0.0340 | 0.1140 | 0.6270 | 0.2590 | | |
| 15.350 0. 0. 1. | 0.3420 | 0.6300 | 0.0280 | 0.0660 | 0.7240 | 0.2100 | | |

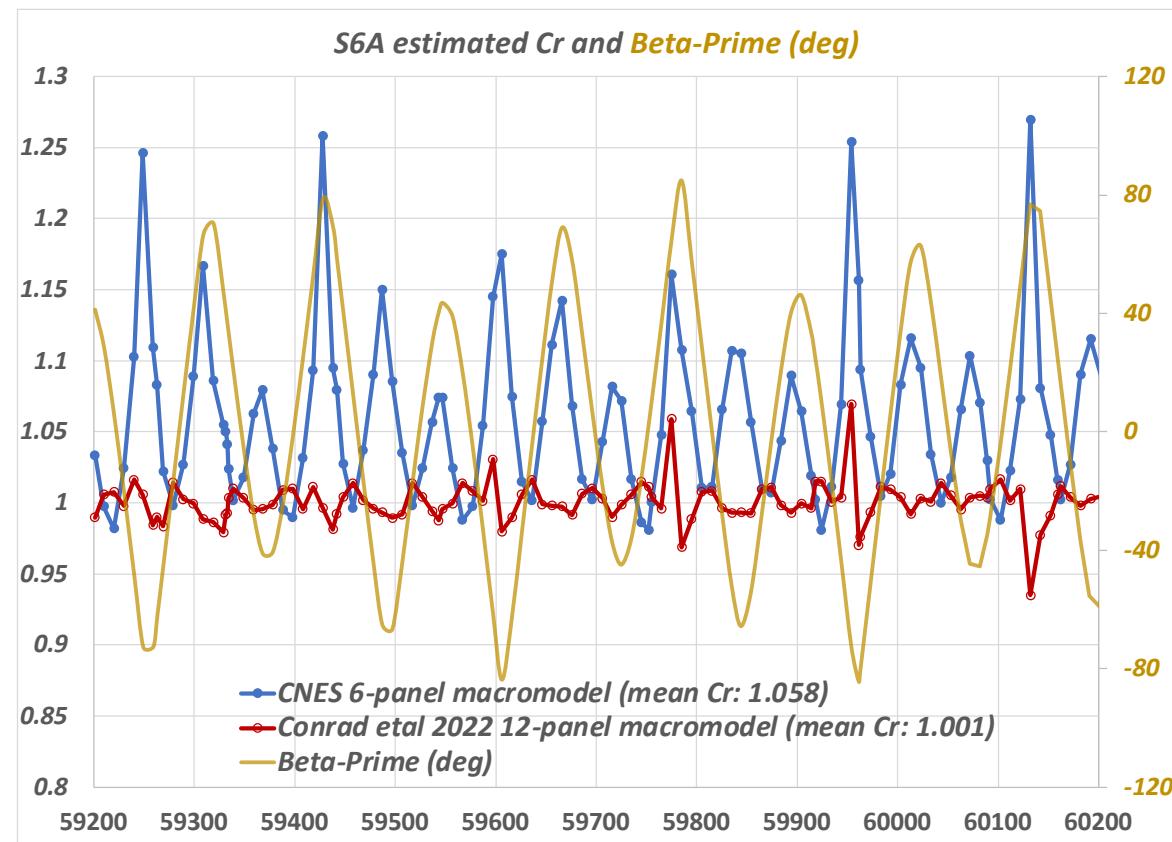
Conrad 12-panel

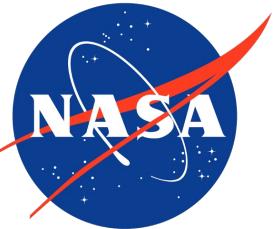
| Surface | Surface normal [x,y,z] | Area (m ²) | Diffusivity | Specularity |
|-------------------|-------------------------|------------------------|-------------|-------------|
| Body +X | [1.000, 0.000, 0.000] | 4.149 | 0.041 | 0.349 |
| Body -X | [-1.000, 0.000, 0.000] | 3.941 | 0.042 | 0.546 |
| Body +Y | [0.000, 1.000, 0.000] | 1.329 | 0.040 | 0.506 |
| Body -Y | [0.000, -1.000, 0.000] | 1.329 | 0.040 | 0.506 |
| Body +Z | [0.000, 0.000, 1.000] | 11.830 | 0.016 | 0.571 |
| Body -Z | [0.000, 0.000, -1.000] | 2.072 | 0.030 | 0.660 |
| Left SP | [0.000, -0.616, -0.788] | 8.65 | 0.316 | 0.139 |
| Right SP | [0.000, 0.616, -0.788] | 8.65 | 0.316 | 0.139 |
| AMR-C (top) | [0.469, 0.000, -0.883] | 0.92 | 0.080 | 0.000 |
| AMR-C (bottom) | [0.000, 0.000, 1.000] | 0.8123 | 0.563 | 0.188 |
| Left SP (bottom) | [0.000, -0.616, 0.788] | 3.760 | 0.164 | 0.013 |
| Right SP (bottom) | [0.000, 0.616, 0.788] | 3.760 | 0.164 | 0.013 |



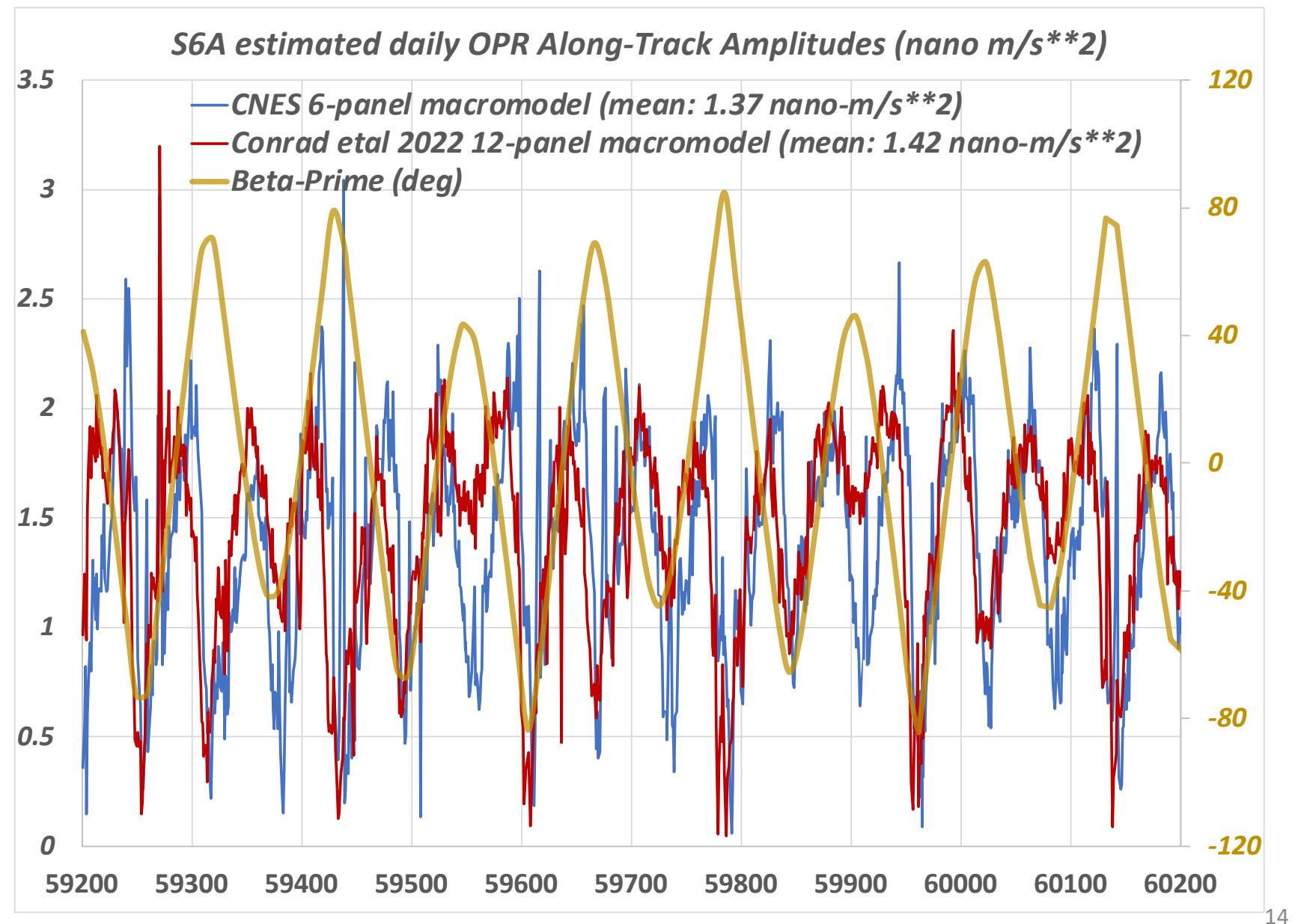
Evaluate Sentinel-6A Conrad 12-panel macromodel (1 of 2)

| S6A tests (201218-231004) | POD residuals | | Radial orbit RMS differences (mm) | | |
|-------------------------------|---------------|----------|--------------------------------------|------------------|---------|
| | DORIS (mm/s) | SLR (mm) | poef | jpl to 230419 | std2300 |
| std2300 | 0.3847 | 6.19 | 6.7 | 5.7 | ---- |
| std2300 Conrad 12-panel model | 0.3866 | 5.99 | 6.5 | 5.8 | 2.5 |





Evaluate Sentinel-6A Conrad 12-panel macromodel (2 of 2) daily OPR along-track amplitudes (nm/s**2)

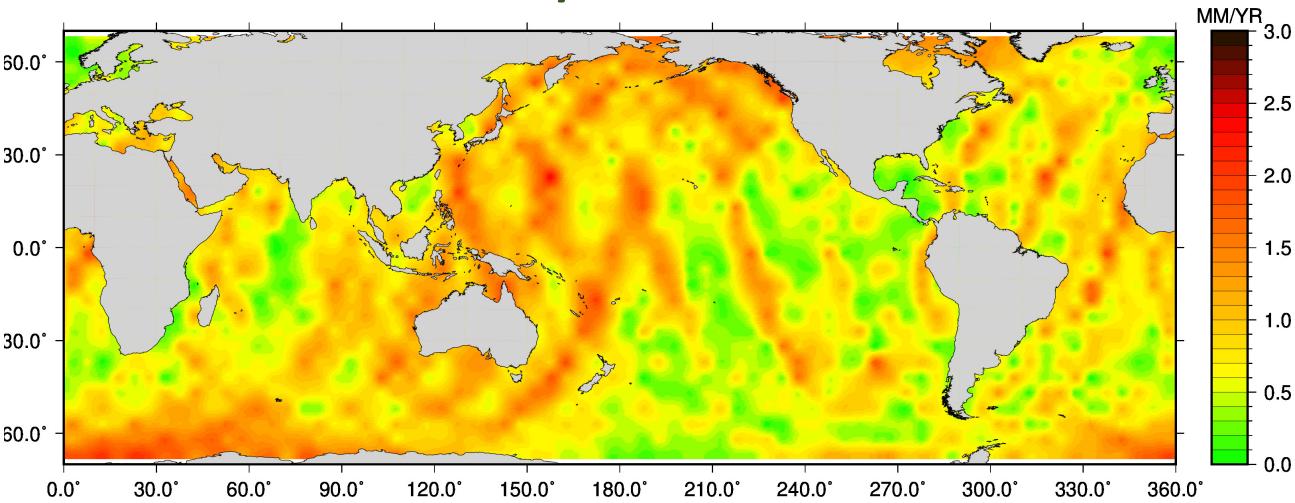




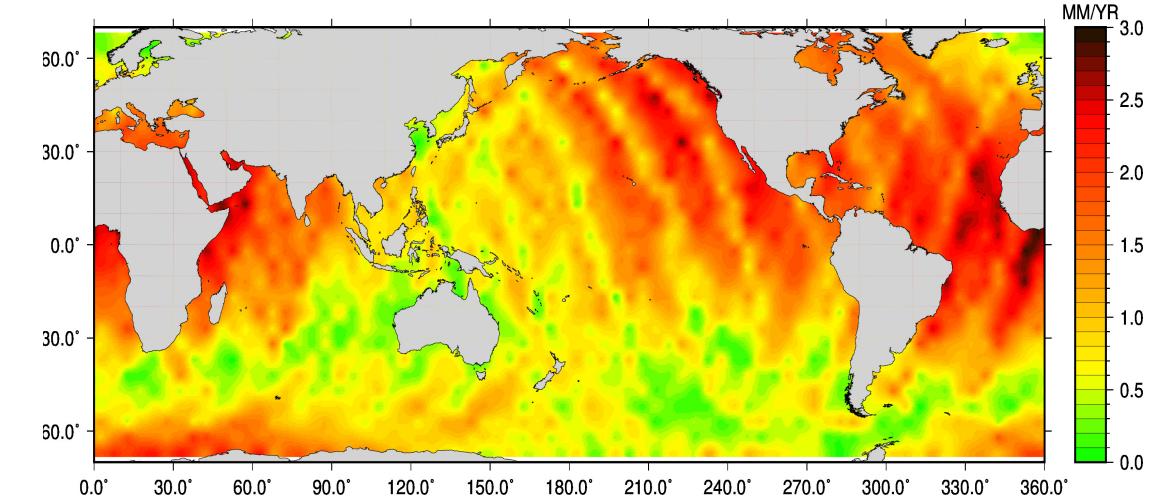
Sentinel-6A JPL-Test geographically-binned radial orbit 59-day signal (mm)



*Sentinel-6A JPL-std2300_conrad orbit 59-day signal
Conrad 12-panel macromodel*



*Sentinel-6A JPL-std2300 orbits 59-day signal
CNES 6-panel macromodel*



Reduction of the 59-day signal suggests Conrad 12-panel macromodel improves surface force modeling over the original CNES 6-panel model.



GSFC GNSS S6A POD with GEODYN:

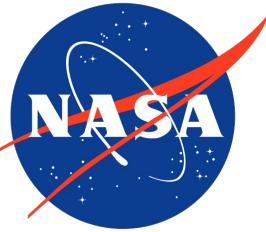
T.C. Thomas, S.B. Luthcke, T.A. Pennington, D.D. Rowlands, ICESat-2 & GEDI POD Team



- S6A POD solutions were generated over 8-month tandem period with JASON-3:**
 - January 1, 2021 (2021-001) – August 31, 2021 (2021-243).
 - Nominal 30-hour ARCs centered on noon of each day; except for spacecraft orbital maneuvers + GPS receiver data gaps (247 ARCs total).

| POD Results Summary | | | | | | | | | | | | | |
|---|------------------|------------------------|-------------------|---------------|-------------------|---|------------------|------------------|------------|----------------------|------------------|------------------|------------|
| Run Description | GPS DD Residuals | | | SLR Residuals | | Consecutive Orbit Overlap Delta (vs. previous ARC) | | | | Delta vs. JPL Orbits | | | |
| | Number Points | Number Weighted Points | Residual RMS (cm) | Number Points | Residual RMS (cm) | Radial (cm) | Cross-Track (cm) | Along-Track (cm) | Total (cm) | Radial (cm) | Cross-Track (cm) | Along-Track (cm) | Total (cm) |
| Baseline | 43,110,123 | 42,166,873 | 0.993 | 62,144 | 1.749 | 0.297 | 0.423 | 0.601 | 0.813 | 0.839 | 1.955 | 2.319 | 3.171 |
| Estimated Offset Vectors + 1°x1° GPS PCV map (Microcosm) | 44,283,742 | 43,204,440 | 0.887 | 62,144 | 1.566 | 0.220 | 0.340 | 0.449 | 0.621 | 0.699 | 1.856 | 2.014 | 2.850 |
| Estimated Offset Vectors + 1°x1° GPS PCV map (GNSS Pre-Processor) | 16,491,229 | 16,020,386 | 0.985 | 62,144 | 1.385 | 0.169 | 0.249 | 0.368 | 0.486 | 0.543 | 1.656 | 1.664 | 2.444 |

- Significant improvement in POD performance achieved through:**
 - Improved measurement modeling: new estimated offset vectors, and application of GPS antenna PCV map.
 - New pre-processing which improves GNSS satellite coverage and pass lengths and significantly eliminates redundant pass geometries.
- Independent SLR Residual RMS improved from 1.75 cm to 1.39 cm.**
- Comparison to JPL red-dyn. orbits improves from 0.84 cm radial RMS to 0.54 cm.**
- The next step is to continue testing Galileo POD with S6A.**



Conclusions

All SLR+DORIS POD preliminary tests showed some improvement over the existing standards (std2006_cs21)

- *ITRF2020-based orbits show slightly better accuracy over the ITRF2014-based, especially over the TOPEX period and from about 2020 (c.f. Sentinel-6A)*
- *GRGS_RL05 gravity orbits show a smaller higher accuracy over the GSFC std2300 gravity, especially over the TP period and from about 2020. Note- the GRGS_RL05 solution for 19500101.0000 to 19930117.0544 is anomalous.*
- *COSTG_FSM S6A orbits suggest a higher accuracy over the GRGS_RL05 orbits, but the COSTG_FSM field is only available from 2018.*
- *The Sentinel-6A Conrad 12-panel macromodel shows some improvement over the CNES 6-panel model, but more testing is needed.*
- *Further improvements are possible including:*
 - *RL07 Ocean & atmosphere dealiasing model.*
 - *GOT5.X ocean tide model for ocean geopotential & ocean loading.*
 - *Apply ITRF2020 Annual terms, or non-tidal loading corrections.*